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Optical Gating with Asymmetric Field Ratios for Isolated Attosecond Pulse Generation

Eric Cunningham and Zenghu Chang

***Abstract*—A technique to improve double optical gating for generating isolated attosecond pulses is introduced. In this method, the ratio between the amplitudes of the counter-rotating pulses is altered to decrease the field strength prior to the linearly-polarized gate cycle. The result is a decrease in the pre-ionization of the gas target used for generating high-order harmonics. In addition to improving phase matching and increasing the saturation intensity, this development also allows isolated attosecond pulse production with longer driving laser pulses.**

***Index Terms*—Optical gating, isolated attosecond pulses, high-harmonic generation, extreme ultraviolet supercontinuum.**

I. Introduction

EXtreme ultraviolet (XUV) and x-ray isolated attosecond pulses are generated using a variety of methods [1]. Under polarization gating (PG) [2]–[6], a linearly-polarized femtosecond laser pulse is transformed into a pair of counter-rotating circularly-polarized pulses. The delay between the peaks of the two pulses can be carefully tailored to create an overlap region in which a single near-linear half-cycle of the laser is surrounded on both sides by regions of quickly-increasing ellipticity. Because high-harmonic generation – responsible for producing the required XUV/x-ray bandwidth – is ellipticity-dependent, attosecond pulse generation is suppressed in the peripheral laser cycles, while a single isolated attosecond pulse can be produced by the near-linear half-cycle.

Physically, this polarization gating can be accomplished using two phase retarders: a multi-cycle delay plate and a zero-order quarter-wave plate. The delay plate is positioned such that its optic axis is rotated $45°$ from the input linear polarization direction. This splits the pulse into two orthogonally-polarized pulses of equal amplitude, where the separation between the peaks of the two pulses is determined by the delay plate's thickness and refractive indices. The zero-order quarter-wave plate, with its fast axis rotated $45°$ from the axis of the first phase retarder, converts the two linear pulses into circularly-polarized pulses with opposite handedness. The overlap of these two pulses yields a "polarization gate": a half-cycle region in which the total field ellipticity is below the threshold ellipticity for high harmonic generation.

While no other cycles contribute to the generation of high harmonics, the laser cycles on the leading edge of the pulse cause unwanted ionization of the gas target before the arrival of the linear cycle. This pre-ionization places a limit on: 1) the longest driving laser pulse duration still capable of generating isolated attosecond pulses, 2) the maximum driving laser intensity at which phase matching conditions can be achieved, and 3) the highest driving laser intensity attainable without depleting the ground state population of the gas target.

Two methods have proven successful at limiting the amount of gas target ionization preceding a polarization gate: **1)** the use of a two-color field [7]–[9] and **2)** the use of elliptically-polarized counter-rotating pulses [10], [11].

First, the addition of a second harmonic field to the polarization-gated field relaxes the constraint on the polarization gate width from half-cycle to full-cycle. This decreases the required separation between the peaks of the two counter-rotating pulses, meaning that fewer ionizing laser cycles precede the arrival of the polarization gate. This technique is called double optical gating (DOG) [7], [8], and it is physically accomplished by making two changes to the PG setup described above. First, the initial phase retarder is changed to decrease the delay between the two counter-rotating pulses. Second, the zero-order quarter-wave plate is replaced with the combination of a (positive uniaxial) phase plate and a (negative-uniaxial) frequency-doubling crystal. By choosing the thicknesses properly, these form a zero-order quarter-wave plate while also generating a second harmonic field.

Second, the utilization of elliptically-polarized counter-rotating pulses (as opposed to circularly-polarized pulses) decreases the amplitude of the laser cycles preceding the polarization gate, thus leading to a reduction in leading-edge ionization. By specifically decreasing the polarization component responsible for generating the isolated attosecond pulse, the ellipticity gate also becomes sharper. This allows the spacing between the two counter-rotating pulses to be decreased, which (as stated earlier) reduces leading-edge ionization by minimizing the number of laser cycles preceding the polarization gate. When this technique is combined with the two-color gating described above, both effects simultaneously reduce leading-edge ionization. Such a gating scheme is called generalized double optical gating (GDOG) [10], [11], and it represents one of the most effective methods to-date for limiting pre-ionization of a gas target. Physically, this is achieved in the DOG setup by attenuating the polarization component $45°$ from the axis of the first phase retarder (typically with glass windows oriented at Brewster's angle θ_B).

In addition to the two approaches described above, we propose a **third** method capable of further limiting the amount of pre-ionization of the gas target. This new technique alters the ratio between the amplitudes of the two counter-rotating circularly- or elliptically-polarized pulses, making the leading

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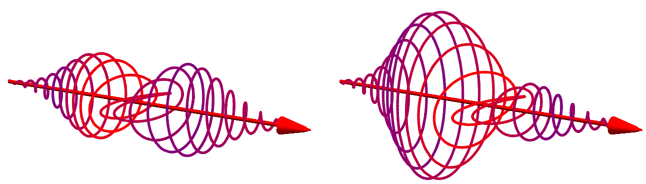
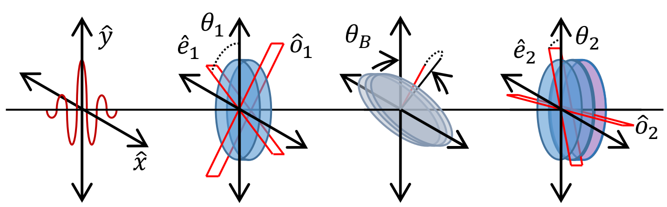
Manuscript received December 1, 2014; revised April 14, 2015.

pulse smaller than the trailing pulse (compare Figs. 1a and 1b). This diminishes the field strength prior to the linearly-polarized laser cycle and shortens the time between the polarization gate and the leading edge of the pulse. The result is a decrease in the pre-ionization of the gas target used for generating isolated attosecond pulses. This technique can be applied to any of the gating methods mentioned above, yielding asymmetric versions of PG, DOG, and GDOG, referred to as APG, ADOG, and AGDOG, that reduce ionization.



(a) Equal field ratio (b) Unequal field ratio



(c) Optics producing a two-color, elliptically-polarized, asymmetric gating field: a phase retarder, Brewster windows, and a zero-order quarter-wave plate made up of a phase retarder and a frequency doubling crystal.

Fig. 1. A typical GDOG setup also allows asymmetric counter-rotating pulses.

II. Physical Apparatus and Gating Parameters

Like the GDOG setup described above, an AGDOG field can be generated using a full-wave phase retarder, Brewster windows, a second phase retarder, and a second harmonic crystal, as depicted in Fig. 1c. The linearly-polarized field incident on this setup can be written as

$$\vec{E}_{\text{input}} = E_0 \exp\left[-2\ln 2\left(\frac{t}{\tau_p}\right)^2\right]\cos\omega t\hat{y} \tag{1}$$

where τ_p is the pulse duration and ω is the carrier frequency.

The first phase retarder splits the field into two orthogonally-polarized pulses separated in time by T_d:

$$\begin{aligned}\vec{E}_{\text{QP1}} &= E_0\cos\omega t\left\{\exp\left[\mathcal{T}_-\right]\cos\theta_1\hat{e}_1 + \exp\left[\mathcal{T}_+\right]\sin\theta_1\hat{o}_1\right\}\\ &= E_0\cos\omega t\left\{\sin\theta_1\cos\theta_1\left(\exp\left[\mathcal{T}_+\right]-\exp\left[\mathcal{T}_-\right]\right)\hat{x}\right.\\ &\qquad\left.+\left(\sin^2\theta_1\exp\left[\mathcal{T}_+\right]+\cos^2\theta_1\exp\left[\mathcal{T}_-\right]\right)\hat{y}\right\} \quad (2)\\ &= E_0\cos\omega t\left\{\left(\sin\theta_1\sin\left(\theta_1-\theta_2\right)\exp\left[\mathcal{T}_+\right]\right.\right.\\ &\qquad\left.+\cos\theta_1\cos\left(\theta_1-\theta_2\right)\exp\left[\mathcal{T}_-\right]\right)\hat{e}_2\\ &\qquad+\left(\sin\theta_1\cos\left(\theta_1-\theta_2\right)\exp\left[\mathcal{T}_+\right]\right.\\ &\qquad\left.\left.-\cos\theta_1\sin\left(\theta_1-\theta_2\right)\exp\left[\mathcal{T}_-\right]\right)\hat{o}_2\right\} \quad (3)\end{aligned}$$

where $\mathcal{T}_\pm \equiv -2\ln 2\left((t\pm T_d/2)/\tau_p\right)^2$ for convenience. Equation 2 has also been re-written in Eq. 3 in the new basis shared by the Brewster windows and the second phase retarder. Because θ_2 is fixed to be $\theta_1 - 45°$ (just as in the case for PG, DOG, and GDOG), Equation 3 can be simplified at the same time the effect of the Brewster windows is accounted for:

$$\begin{aligned}\vec{E}_{\text{BW}} = \frac{E_0}{\sqrt{2}}\cos\omega t&\left\{\epsilon\left(\sin\theta_1\exp\left[\mathcal{T}_+\right]+\cos\theta_1\exp\left[\mathcal{T}_-\right]\right)\hat{e}_2\right.\\ &\left.+\left(\sin\theta_1\exp\left[\mathcal{T}_+\right]-\cos\theta_1\exp\left[\mathcal{T}_-\right]\right)\hat{o}_2\right\} \quad (4)\end{aligned}$$

where ϵ refers to the ellipticity induced by the attenuation of the Brewster windows.

The $\hat{e}_2$ and $\hat{o}_2$ terms can be identified as the driving and gating fields, respectively. Taking into account the zero-order quarter wave plate (second phase retarder and frequency doubling crystal combination), the field can be broken down as follows:

$$E_{drive} = \epsilon\frac{E_0}{\sqrt{2}}\left(\sin\theta_1\exp\left[\mathcal{T}_+\right]+\cos\theta_1\exp\left[\mathcal{T}_-\right]\right) \tag{5}$$

$$E_{gate} = \frac{E_0}{\sqrt{2}}\left(\sin\theta_1\exp\left[\mathcal{T}_+\right]-\cos\theta_1\exp\left[\mathcal{T}_-\right]\right) \tag{6}$$

$$E_{tot} = \sqrt{\left|E_{drive}\cos\left(\omega t\right)\right|^2+\left|E_{gate}\cos\left(\omega t+\pi/2\right)\right|^2} \tag{7}$$

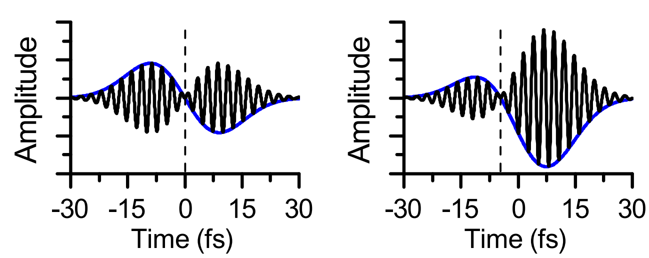
It is evident that tuning θ_1 adjusts the field ratio between the front and back pulse. When $\theta_1 = 45°$, the $\exp\left[\mathcal{T}_-\right]$ and $\exp\left[\mathcal{T}_+\right]$ pulses have equal magnitude, and Eqs. 5 and 6 reduce to the standard expressions for GDOG fields. When $\theta_1 \neq 45°$, the electric field is not projected onto the slow and fast axes of the first phase retarder in equal proportion, and the size of the first pulse (transmitted along the fast axis) is effectively changed relative to the second pulse (transmitted along the slow axis). In order to tune θ_1 while maintaining the fixed $45°$ angle between θ_1 and θ_2, either 1) a zero-order half-wave plate must be added before the first phase retarder or 2) all gating optics must be rotated around the axis given by the propagation direction.

A. Effect on polarization gate position t_c

When the ratio between the amplitudes of the two counter-rotating pulses changes, the location of the polarization gate moves closer to the smaller side of the pulse (see Fig. 2). To determine how the gate position in time changes with θ_1, the time $t = t_c$ must be found for which the gating field E_{gate} becomes zero. Using Eq. 6, it follows that

$$t_c = \frac{\tau_p^2}{T_d}\frac{\ln(\tan\theta_1)}{4\ln 2} \tag{8}$$

When $\theta_1 = 45°$, this expression reduces to $t_c = 0$, as expected in the cases of PG, DOG, and GDOG.



(a) $t_c = 0$ for 1:1 ratio (b) $t_c < 0$ for 3:1 ratio

Fig. 2. Field asymmetry moves the relative position of the polarization gate.

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B. Effect on pulse separation T_d

In order to isolate a single attosecond pulse, the time-dependent field ellipticity $\xi(t)$ at either side of the polarization gate must reach a threshold ellipticity ξ_{th} above which the electron recombination in HHG is strongly suppressed [12]. Mathematically, this requirement is expressed as

$$\xi\left(t = t_c \pm \frac{\delta t_G}{2}\right) = \xi_{th} \tag{9}$$

where t_c is the position in time of the center of the polarization gate, and the width of the polarization gate δt_G is either half of an optical cycle (when using a single-color field) or a full optical cycle (when using a two-color field).

Because the gating field E_{gate} is always bigger than the driving field E_{drive} in the vicinity of the polarization gate, the time-dependent ellipticity $\xi(t)$ itself can be defined as

$$\begin{aligned}\xi(t) \equiv \frac{E_{gate}}{E_{drive}} &= \frac{\frac{E_0}{\sqrt{2}}\left(\sin\theta_1 \exp\left[\mathcal{T}_+\right] - \cos\theta_1 \exp\left[\mathcal{T}_-\right]\right)}{\epsilon\frac{E_0}{\sqrt{2}}\left(\sin\theta_1 \exp\left[\mathcal{T}_+\right] + \cos\theta_1 \exp\left[\mathcal{T}_-\right]\right)} \\ &= \frac{1}{\epsilon}\frac{\left(\tan\theta_1 - \exp\left[\mathcal{T}_- - \mathcal{T}_+\right]\right)}{\left(\tan\theta_1 + \exp\left[\mathcal{T}_- - \mathcal{T}_+\right]\right)}\end{aligned} \tag{10}$$

Applying the condition given in Eq. 9 to Eq. 10, an expression can be derived for the pulse separation T_d necessary for achieving a suitable polarization gate:

$$\begin{aligned}\xi_{th} &= \frac{1}{\epsilon}\frac{\left(\tan\theta_1 - \exp\left[4\ln 2\frac{T_d}{\tau_p^2}(t_c \pm \delta t_G/2)\right]\right)}{\left(\tan\theta_1 + \exp\left[4\ln 2\frac{T_d}{\tau_p^2}(t_c \pm \delta t_G/2)\right]\right)} \\ &\Rightarrow 4\ln 2\frac{T_d}{\tau_p^2}\left(t_c \pm \frac{\delta t_G}{2}\right) = \ln\left(\tan\theta_1 \frac{1-\epsilon\xi_{th}}{1+\epsilon\xi_{th}}\right)\end{aligned} \tag{11}$$

Inserting the expression for t_c given in Eq. 8 leads to

$$\begin{aligned}\pm 2\ln 2\frac{T_d \delta t_G}{\tau_p^2} + \ln\left(\tan\theta_1\right) &= \ln\left(\tan\theta_1\right) + \ln\left(\frac{1-\epsilon\xi_{th}}{1+\epsilon\xi_{th}}\right) \\ \Rightarrow T_d &= \pm\frac{1}{2\ln 2}\frac{\tau_p^2}{\delta t_G}\ln\left(\frac{1-\epsilon\xi_{th}}{1+\epsilon\xi_{th}}\right)\end{aligned} \tag{12}$$

where the plus/minus simply indicates that the same ellipticity is achieved regardless of which pulse comes first. Notice that Eq. 12, independent of θ_1, is identical to the formula used to calculate the requisite pulse separation for GDOG.

It is also interesting to note that by inserting Eq. 12 into Eq. 8, it is seen that the position of the polarization gate t_c is *not* a function of the pulse duration τ_p:

$$t_c = \frac{\tau_p^2}{T_d}\frac{\ln(\tan\theta_1)}{4\ln 2} = \pm\frac{\delta t_G}{2}\frac{\ln(\tan\theta_1)}{\ln\left(\frac{1+\epsilon\ \xi_{th}}{1-\epsilon\ \xi_{th}}\right)} \tag{13}$$

C. Effect on HHG-producing field amplitude $E_{drive}(t = t_c)$

The intensity of the laser inside the polarization gate is also affected by the ratio between the two counter-rotating pulses. In order to scale this intensity to a specific value for appropriately comparing different gating schemes, the electric field amplitude E_0 must be expressed as a function of the driving field strength at $t = t_c$. From Eq. 5, it follows that

$$E_0 = \frac{E_{drive}(t_c)}{\epsilon\sqrt{\sin 2\theta_1}}\exp\left[2\ln 2\left(\frac{t_c^2 + \frac{T_d^2}{4}}{\tau_p^2}\right)\right] \tag{14}$$

In order to isolate the effect of the field asymmetry, the ratio is taken between the two instances of Eq. 14 where $\theta_1 \neq 45°$ (asymmetric field) and $\theta_1 = 45°$ (symmetric field):

$$\frac{E_0(\theta_1 \neq 45°)}{E_0(\theta_1 = 45°)} = \frac{1}{\sqrt{\sin 2\theta_1}}\left(\tan\theta_1\right)^{\frac{1}{8\ln 2}\frac{T_d^2}{\tau_p^2}\ln\left(\tan\theta_1\right)} \tag{15}$$

Figure 3 plots Eq. 15 using parameters that simulate an 800 nm driving laser gated by one of three different methods: APG ($\tau_p = 7$ fs), ADOG ($\tau_p = 20$ fs), and AGDOG ($\epsilon = 0.5$, $\tau_p = 28$ fs). The resulting coefficients are plotted in red, green, and blue, respectively. Because pulse energy is proportional to the modulus squared of the electric field, a scaling factor of $\sqrt{2}$ means that the original pulse energy needs to be twice as large to keep the same driving field intensity at $t = t_c$.

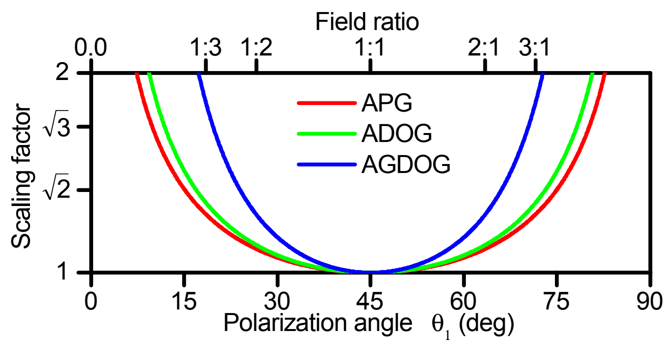

Fig. 3. Scaling factors required to maintain a constant driving field intensity inside the polarization gate as the field asymmetry is changed.

Figure 3 depicts the "cost" of field asymmetry variation – the amount of additional pulse energy needed to scale the polarization gate intensity when θ_1 changes. This can be compared to the "cost" of varying the field ellipticity ϵ, which can be expressed by taking the ratio between the two instances of Eq. 14 where the ellipticity ϵ is variable (elliptically-polarized case) and $\epsilon = 1$ (circularly-polarized case). Figure 4 plots this ratio using the same pulse durations and gating methods as in Fig. 3, except this time the ellipticity is varied and the field ratio is symmetric ($\theta_1 = 45°$): generalized PG or GPG ($\tau_p = 7$ fs, in red), GDOG ($\tau_p = 20$ fs, in green), and GDOG ($\tau_p = 28$ fs, in blue). From this analysis, it is evident that the "cost" of using field asymmetry is low compared to that of using field ellipticity.

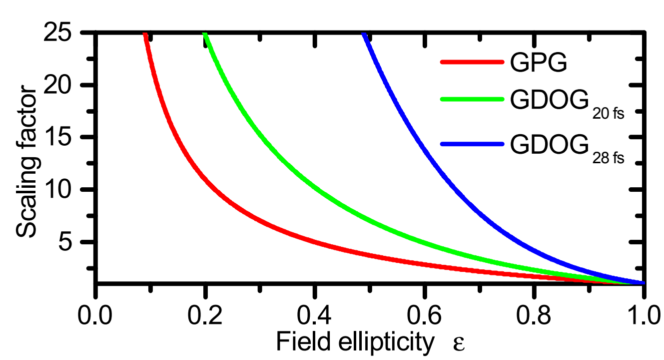

Fig. 4. Scaling factors required to maintain a constant driving field intensity inside the polarization gate as the field ellipticity is changed.

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III. Simulations

To examine how field asymmetry influences the fundamental physical limit of the field intensity on pre-ionization in the single-atom picture, several simulations were performed using the ADK ionization rate [13], which is given by

$$w_{ADK} = |C_{n^\star l^\star}|^2 G_{lm} I_p \left(\frac{2F_0}{E_{tot}}\right)^{\Xi} \exp\left(-\frac{2}{3}\frac{F_0}{E_{tot}}\right) \quad (16)$$

where $\Xi = 2n^\star - |m| - 1$, E_{tot} is given by Eq. 7, and the parameters $|C_{n^\star l^\star}|^2$, G_{lm}, I_p, F_0, $n^\star$, $l^\star$, l, and m are constants unique to the chosen target element [14]. From Eq. 16, the ionization probability of a targeted atom at time t is calculated by integrating:

$$P(t) = 1 - \exp\left[\int_{-\infty}^{t} w_{ADK}(t')dt'\right] \quad (17)$$

In order to make a fair comparison between the pre-ionization associated with different gating schemes, the intensity inside the polarization gate is kept constant for all simulations using Eq. 14. Note, however, that this expression only insures that the *envelope* of the driving field E_{drive} remains the same for different values of θ_1. Thus for simulation purposes, it is necessary to specify the phase of the carrier wave to guarantee that the full driving field $E_{drive}\cos(\omega t + \boldsymbol{\phi_{CE}})$ is always maximum at the center of the gate. This is achieved by adjusting the value of the carrier-envelope phase ϕ_{CE} as a function of the gate center t_c:

$$\begin{aligned} &\cos(\omega t_c + \phi_{CE}) = 1 \\ \Rightarrow \quad &\phi_{CE} = -\omega t_c = -\omega \frac{\tau_p^2}{T_d}\frac{\ln(\tan\theta_1)}{4\ln 2} \end{aligned} \quad (18)$$

Figure 5 shows an example of an ADK simulation comparing GDOG and AGDOG (3:1 ratio, expressed hereafter using subscripts). Here, the composite fields ionize argon with a polarization gate intensity of $2.19 \times 10^{14} \mathrm{W/cm^2}$, corresponding to a theoretical XUV photon cut-off of 57 eV (matching the spectral edge in the reflection curve for a Brewster-angled silicon XUV-IR beam splitter). In both cases, an 800 nm, 20 fs driving laser pulse is assumed, and the ellipticity $\epsilon = 0.5$.

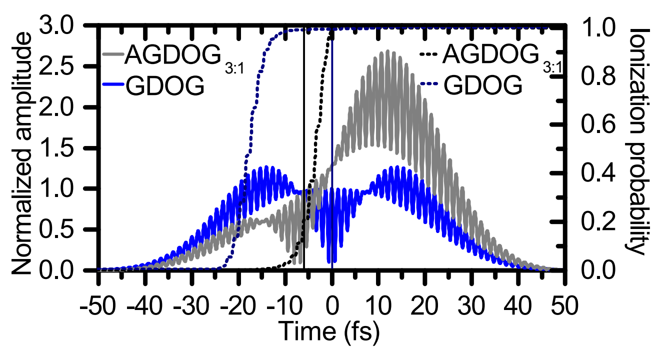

Fig. 5. Predicted ionization rates in argon with GDOG and AGDOG$_{3:1}$ fields ($\lambda = 800$ nm, $\tau_p = 20$ fs, $\epsilon = 0.5$, $I_{gate} = 2.19 \times 10^{14}$ W/cm^2).

In the case of GDOG (blue), the ionizing field saturates the target more than 10 fs before the arrival of the polarization gate, meaning that no neutral atoms remain to generate an isolated attosecond pulse. Alternatively, the asymmetric ionizing field (gray) is smaller leading up to the polarization gate, which itself arrives ∼6 fs earlier than in the GDOG case. As a result, the ionization probability at the polarization gate (black) is less than 10% – a dramatic improvement in the limitation of target pre-ionization as compared to the symmetric field.

In general, this suppression of pre-ionization leads to three potential benefits: 1) production of isolated attosecond pulses with longer driving pulse durations, 2) phase matching at higher photon energies, and 3) extension of the theoretical cut-off of the XUV continuum.

A. Longer Driving Pulse Duration

To provide an example of the effectiveness of field asymmetry in limiting ionization, a set of simulations is carried out calculating the expected ionization probability at the polarization gate as a function of the driving pulse duration when using PG, DOG, GDOG, and AGDOG$_{3:1}$. In the case plotted in Fig. 6, the polarization gate intensity of the 800 nm pulses is held constant at 2.8×10^{14} W/cm^2, which can produce XUV photons with argon up to the edge of the transmission window of aluminum near 70 eV. According to the simulation, AGDOG remains serviceable for much longer pulse durations than any other gating strategy.

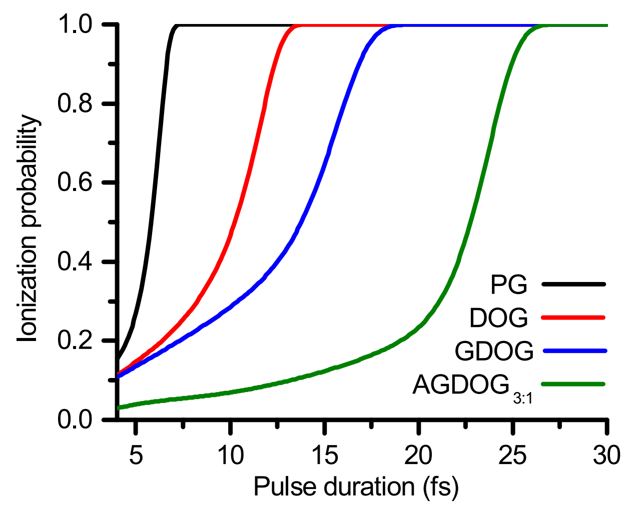

Fig. 6. Predicted ionization rates in argon with different gating schemes as a function of pulse duration ($\epsilon = 1$ (PG, DOG) or $\epsilon = 0.5$ (GDOG, AGDOG), $\lambda = 800$ nm, $I_{gate} = 2.8 \times 10^{14}$ W/cm^2).

B. Improved Phase Matching

In noble gas atoms, phase matching can usually occur when only a few percent of the target atoms are ionized [15]. To operate in such a regime, the laser pulse must be relatively weak, which consequently limits the highest intensity achievable inside the polarization gate. This in turn determines the maximum HHG photon energy that can be phase-matched.

To compare the phase matching cut-off allowable by different gating schemes, the ionization rate is simulated using the ADK model, and a gate intensity is found which ionizes the correct percentage of the generation gas necessary for phase

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matching. The theoretical HHG photon energy cut-off for such an intensity is then calculated using $E_{max} = I_p + 3.17U_p$, where I_p is the ionization potential and U_p is the ponderomotive potential [16].

Figure 7 compares the phase matching cut-off of PG, DOG, GDOG, and $\text{AGDOG}_{3:1}$ in argon gas ($P_{PM} = 3.8\%$, $I_p = 11.6$ eV) as a function of pulse duration. For these parameters, the AGDOG field allows for an increase in the phase matching cut-off of ∼10 eV.

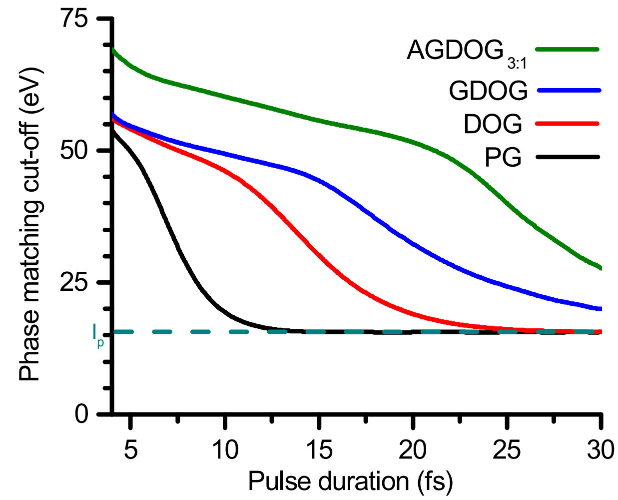

Fig. 7. The XUV cut-off energy associated with the highest polarization gate intensity that does not result in ionization surpassing the criteria for phase matching ($\epsilon = 1$ (PG, DOG) or $\epsilon = 0.5$ (GDOG, AGDOG), $\lambda = 800$ nm).

C. Higher Saturation Intensity

In noble gas atoms, saturation is said to occur when 97% of the target atoms are ionized. This corresponds to the strongest possible laser field usable before isolated attosecond pulse generation is frustrated inside the polarization gate by an insufficient number of neutral atoms remaining in the target. This leads to the maximum XUV photon energy achievable by the gated laser field.

To compare the uppermost cut-off allowable by different gating schemes, the ionization rate is simulated using the ADK model, and a gate intensity is found which ionizes the target up to the point of saturation. The theoretical HHG photon energy cut-off for such an intensity is then calculated again using $E_{max} = I_p + 3.17U_p$.

Figure 8 compares the saturation cut-off of PG, DOG, GDOG, and $\text{AGDOG}_{3:1}$ in argon gas as a function of pulse duration. For these parameters, the AGDOG field allows for an increase in the saturation cut-off from ∼10 eV for long pulse durations to over ∼50 eV for short pulse durations.

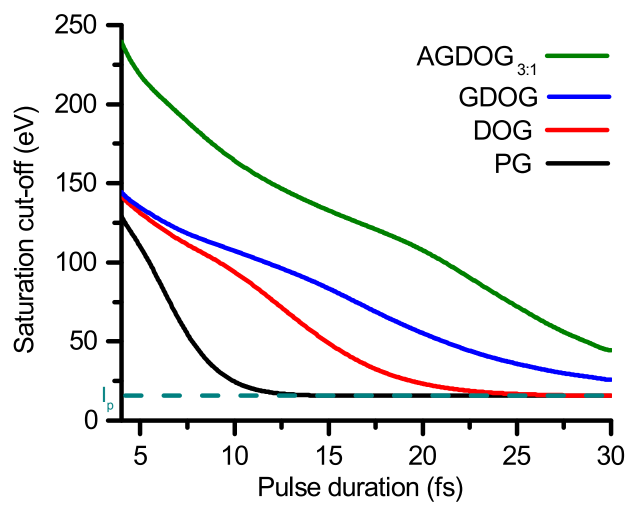

Fig. 8. The XUV cut-off energy associated with the highest polarization gate intensity that does not result in ionization surpassing the criteria for saturation ($\epsilon = 1$ (PG, DOG) or $\epsilon = 0.5$ (GDOG, AGDOG), $\lambda = 800$ nm).

IV. Conclusion

The use of asymmetric counter-rotating pulses in polarization-based gatings has been introduced as means to decreasing ionization before the arrival of the polarization gate. Strong field simulations (in preparation elsewhere) indicate that this improvement in performance comes with no change to the characteristics of the HHG when comparing the asymmetric and symmetric cases.

Each of the three primary benefits mentioned – 1) the use of longer driving pulse durations, 2) the improvement of phase matching, and 3) the increase in achievable XUV photon energies – has its own implications. **First**, allowing the use of longer driving laser pulses makes the field of attoscience accessible by a broader range of laser systems. Because few-cycle lasers are difficult to achieve, attosecond research is currently limited to laboratories that can support such specialty laser systems. On the other hand, many-cycle laser pulses (e.g. >35 fs at 800 nm) are commonplace, thus potentially allowing isolated attosecond pulse production from many turn-key commercial ultrafast laser systems, homemade table-top systems in low-budget laboratories, and even large-scale petawatt laser facilities. The relaxation of the pulse duration requirement may also allow isolated attosecond pulse generation using lasers based on amplification media that do not possess a gain bandwidth broad enough to support few-cycle pulse generation (e.g. fiber-based systems). **Second**, improving phase matching can aid in the development of high-flux attosecond sources required for exploring nonlinear XUV phenomena or performing attosecond pump–attosecond probe experiments. **Third**, a higher saturation intensity means the generation of larger XUV bandwidths, allowing the isolated attosecond pulses to access new energy regions when performing pump-probe experiments. Additionally, higher driving laser intensities result in attosecond pulses with less atto-chirp; combined with the broader bandwidth, shorter attosecond pulses may be produced if the remaining atto-chirp is properly compensated [17].

Acknowledgment

This work is funded by the National Science Foundation under grant no. 1068604, the Army Research Office, and the DARPA PULSE program by a grant from AMRDEC.

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